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Transport Characteristics of Selected PWR LOCA Generated Debris

Introduction

In the unlikely event of a Loss of Coolant Accident (LOCA) in a pressurized water reactor (PWR), break jet impingement would dislodge thermal insulation from nearby piping, as well as other materials within the containment, such as paint chips, concrete dust, and fire barrier materials. Steam/water flows induced by the break and by the containment sprays would transport debris to the containment floor. Subsequently, debris would likely transport to and accumulate on the suction sump screens of the emergency core cooling system (ECCS) pumps, thereby potentially degrading ECCS performance and possibly even failing the ECCS.

In 1998, the U. S. Nuclear Regulatory Commission (NRC) initiated a generic study (Generic Safety Issue -191) to evaluate the potential for the accumulation of LOCA related debris on the PWR sump screen and the consequent loss of ECCS pump net positive suction head (NPSH) [Ref. x]. Los Alamos National Laboratory (LANL), supporting the resolution of GSI-191, was tasked with developing a method for estimating debris transport in PWR containments to estimate the quantity of debris that would accumulate on the sump screen for use in plant specific evaluations.

The analytical method proposed by LANL, to predict debris transport within the water that would accumulate on the containment floor, is to use computational fluid dynamics (CFD) combined with experimental debris transport data to predict debris transport and accumulation on the screen. CFD simulations of actual plant containment designs would provide flow data for a postulated accident in that plant, e.g., three-dimensional patterns of flow velocities and flow turbulence. Small-scale experiments would determine parameters defining the debris transport characteristics for each type of debris. The containment floor transport methodology will merge debris transport characteristics with CFD results to provide a reasonable and conservative estimate of debris transport within the containment floor pool and subsequent accumulation of debris on the sump screen. The complete methodology will, of course, include a means of estimating debris generation, transport to the containment floor, transport to the sump screen, and the resulting loss of NPSH.

A panel was convened to identify the important phenomena associated with debris transport on the containment floor. This panel produced a table known as the phenomena identification and ranking table (PIRT) [Ref. x]. Based on the PIRT combined with preliminary CFD analyses, LANL determined the physical processes governing the transport of debris on the containment floor. These processes include: the settling of debris in turbulent pools, tumbling/sliding of settled debris along the floor, re-entrainment of debris from the containment floor, lifting of debris over structural impediments, retention of debris on the vertical screens, and the destruction of debris due to sump pool dynamics, thermal, and chemical effects.

The experimental program described herein was designed to gather data on these transport processes. These tests were conducted at the University of New Mexico (UNM) Open-Channel Hydrology Laboratory. The ranges of experimental parameters and the types of insulation that needed testing were based on a survey of the U. S. PWR plants and CFD simulations of volunteer plants. Potential debris in U. S. PWR plants include various combinations of fibrous, particulate, or metallic thermal insulations, fire-barrier materials, and miscellaneous debris, such as paint chips, concrete dust. The specific materials selected for testing at UNM included: Nukon, Thermal Wrap, Kawool, calcium silicate, aluminum and stainless steel RMI, paint chips, silicone foam and Marinite board.

TEST APPARATUS

The primary test apparatus used to conduct these tests was a relatively large linear flume. The large flume was designed as a separate-effects test apparatus to simulate a variety of flow conditions and to study debris transport under these conditions. The flume consisted of a sturdy open-top box 20-ft long, 3-ft wide, and 4-ft high with Plexiglas side panels for viewing the transport of debris. The large flume rested on two sturdy 6-inch by 6-inch aluminum I-beams that in turn rested on the UNM 50-ft long tilting table where hydraulic jacks were used to level the table. The first 6-ft of the flume was reserved for the water inlet and flow conditioning apparatus and the final 4-ft section was reserved for a debris catcher screen and the outlet drain. This left a central 10-ft section available for testing. The water surface was a free flowing surface. The floor of the flume was coated with an epoxy liner to obtain a surface roughness comparable to an epoxy coated PWR floor and the flume was wide enough to negate wall-effects. The walls and floor sections were held together with a sturdy steel framework. A variable speed centrifugal pump capable of 2200 GPM pumped water from the sump to overhead piping to the test apparatus. At the rear of the flume, water drained through an outlet pipe back into the sump. The flow velocity was thus variable to velocities up to and beyond 1.5 ft/sec. The large flume is shown in Photo 1.

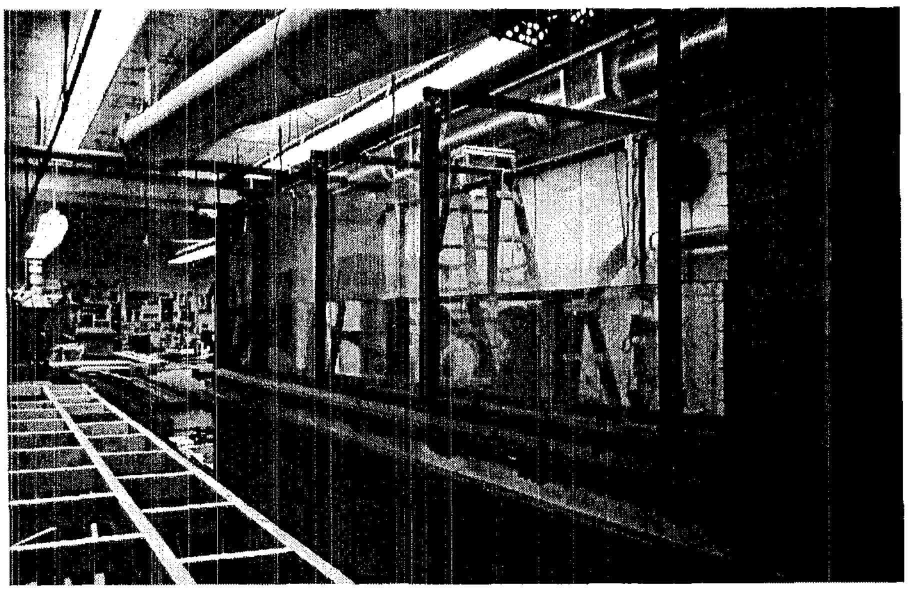

Photo 1. Large Flume Test Apparatus

A range of pool flow dynamics would likely exist in a containment floor pool following a postulated LOCA accident, i.e., from quiescent or nearly still water to extremely turbulent water. A goal of the large flume testing was to explore the effect of inlet flow patterns and fluid residual turbulence on the transport of debris. To achieve this goal, flow straighteners and diffusers were used to condition the flow prior to its entering the test section. The conditioning method depended upon the type of test being conducted. Three methods of inlet flow conditioning were used in the large flume tests. These methods were: 1) Configuration A: Diffused Flow Entry, 2) Configuration B: Free Fall Flow Entry, and 3) Configuration C: Immersed Pipe Flow Entry. An extensive effort was devoted for understanding types of flow patterns established in the flume for these different operating conditions, both experimentally and using CFD simulations of the large flume.

In Conditioning Method A, flow turbulence was extensively dampened to provide a uniform quiescent flow throughout the test section. Therefore, the local flow velocities were unidirectional and well represented by the average flow velocity. In this manner, the local conditions affecting the transport of individual pieces of debris were well known, i.e., debris transport could be correlated with the flow conditions affecting that piece of debris. On the other hand, Conditioning Methods B and C provided two different types of three-dimensional inlet flow conditioning that retained both non-uniformities and turbulence affecting debris transport. In this manner, the impact of flow turbulence could be realistically assessed. With non-uniform flow conditioning, the local flow velocity affecting an individual piece of debris was not necessarily represented by the average flow velocity.

In Conditioning Method A, the diffused flow entry was achieved by implementing a series of damping pads followed by a flow straightener. The damping pads were actually synthetic air-conditioning humidifier pads held in place by #4 wire mesh attached to wooden frames. A dampening section consisted of a total of five wooden frames holding four humidifier pads in-between. The sheet-metal lattice-structured flow straightener furthered straightened the flow. The dimensions of the straightener assembly were 3-ft by 4-ft to fit within the flume cross-section, and 1-ft thick with 3-inch square lattice cells. The flow conditioner section, for Configuration A, is shown in Photo 2.

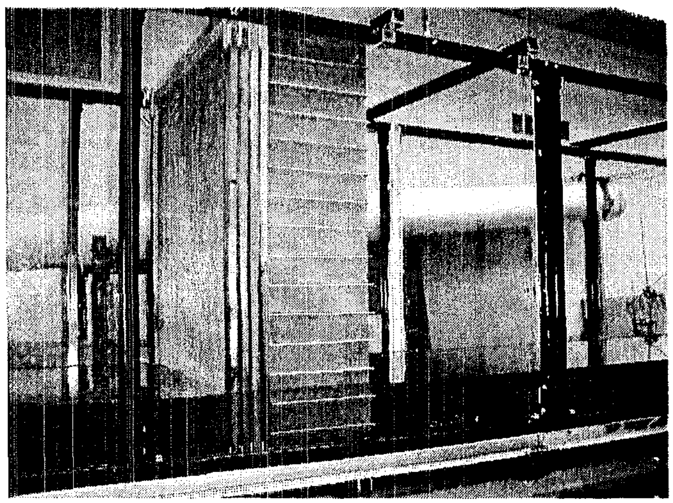

Photo 2. Diffuse Flow Entry Flow Conditioning Section

Considerable flow visualization/characterization testing was done to develop this hardware configuration. Conventional techniques such as dye injection and tracer particle tracking were used to visually establish that flow patterns were straight and that no visible eddies existed in the test section. In addition local flow velocities were measured at several horizontal and vertical locations to ensure that flow entering the test section was straight and that no unusual flow patterns existed. These measurements relied on 'neutrally buoyant water balloons' at low flow rates and 'pigmy' type turbine flow meters at the higher flow rates through the flume.

In addition, CFD modeling of the flume flow patterns was also undertaken to further assure that flow patterns were as intended. These models also confirmed that flow patterns expected for this configuration were uniform, although slightly faster flow occurred near the top surface. For example, a CFD simulation for diffuse flow entry is shown in Figure 1, which illustrated uniform flow in the test section even though the inlet section and, to a lesser extent, the outlet section were highly non-uniform and turbulent. The CFD analytical results were in good qualitative agreement with the experiment flow-visualization results.

Finally, experiments conducted in the large flume to measure tumbling velocity of regularly cut pieces of low-density fibrous insulation were compared with data obtained in other USI A-43 studies [Ref. x] for similar pieces and test data obtained from the small flume. These comparisons further established that flow patterns in the flume corresponding to Conditioning Method A were calm, straight and free of eddies.

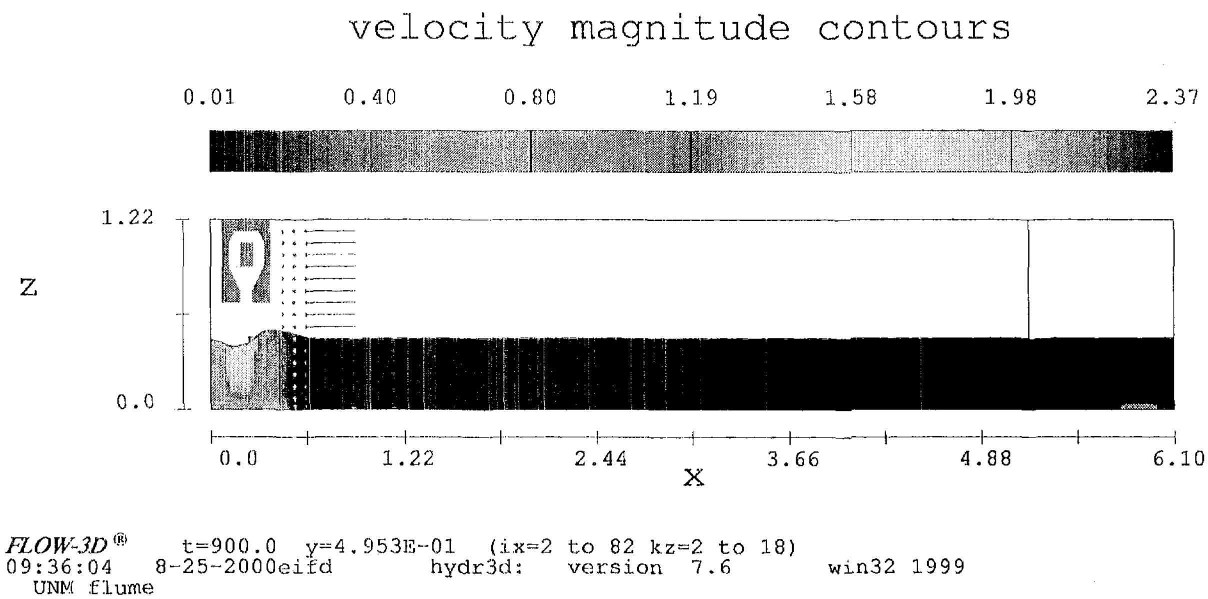

Figure 1. Example CFD Result for the Diffuse Flow Conditioning Configuration

In flow Conditioning Methods B and C, the series of dampening pads were removed leaving only the flow straightener to condition the flow, however, their method of introducing water to the inlet section differed. In Method B, the water was allowed to freefall from the pipe exit located approximately 2-ft above the water surface. Flow measurements suggested that a fast moving water layer existed at the bottom and further that the flow field was dominated by large-scale eddies. The location and extent of these eddies appeared to shift closer to the sump as flow rate was increased. Qualitatively at least it could be stated that the flow patterns were in agreement with those predicted by the CFD analyses. They also appeared to capture many of the important aspects of the flow patterns predicted by the CFD analyses for 'exposed sump' geometry. In Method C, the inlet water pipe was extended to exit 1-ft from the flume floor and the pipe diameter was reduced from 10-inches to 6-inches. Thus, Method C provided a different three-dimensional flow pattern than that of Method B.

A screen filtered the water flow leaving the large flume test section. This screen both filtered the water before it was returned to the sump and provided a means of measuring head loss associated with debris buildup on a screen. This screen was constructed from commercially available screening material. The weave of this screen created diamond shaped cells that were approximately ¼-inch wide by 1/8-inch height[1]. The screen was supported by a section of standard-use grating located directly behind the screen.

Floor obstructions in the form of 'curbs' were attached to the flume floor in selected tests to simulate curbs found in nuclear power plants. These curbs were placed just in front of the

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[1] Note that features of the screen (e.g., clearance size) were immaterial to the experiments conducted. Screen facial roughness was somewhat important because it influenced debris detachment velocity. From that point of view, the selected screen resembled PWR screens closely in that it offered a smooth surface without observable dimples or other such geometrical features that induced unrealistic friction.

screen, were about 2-inches thick, and either 2-inches or 6-inches in height. Photo 3 shows a typical curb in the standard test section along with the lower portion of the debris catch screen.

In selected tests, the flow cross section was altered to force the flow to accelerate by converging the sidewalls to examine the impact, if any, that accelerating water velocities had on debris transport. The channel width from 3-ft down to 1-ft at the downstream screen over a length of 8-ft, thus the cross-sectional flow area was linearly decreased. The converging channel apparatus is shown in Photo 4.

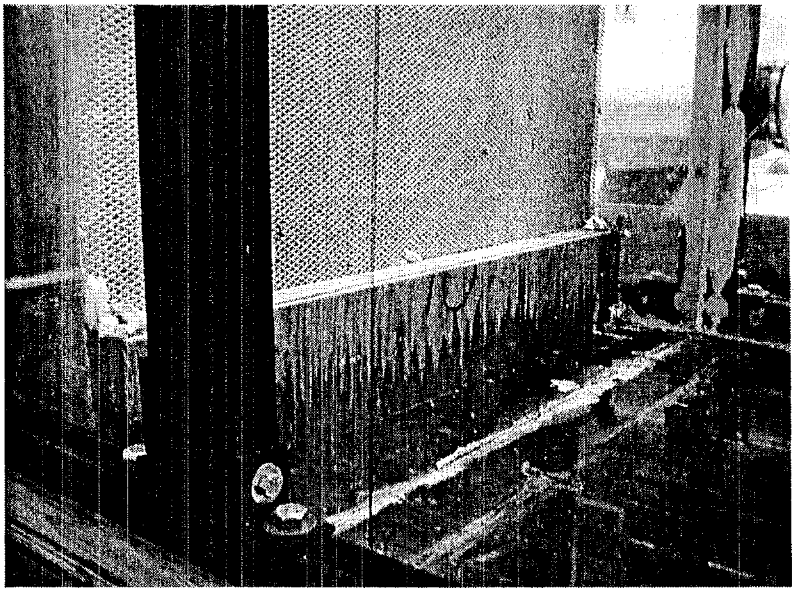

Photo 3. Test Obstruction Curb (6-inch) and Debris Catch Screen

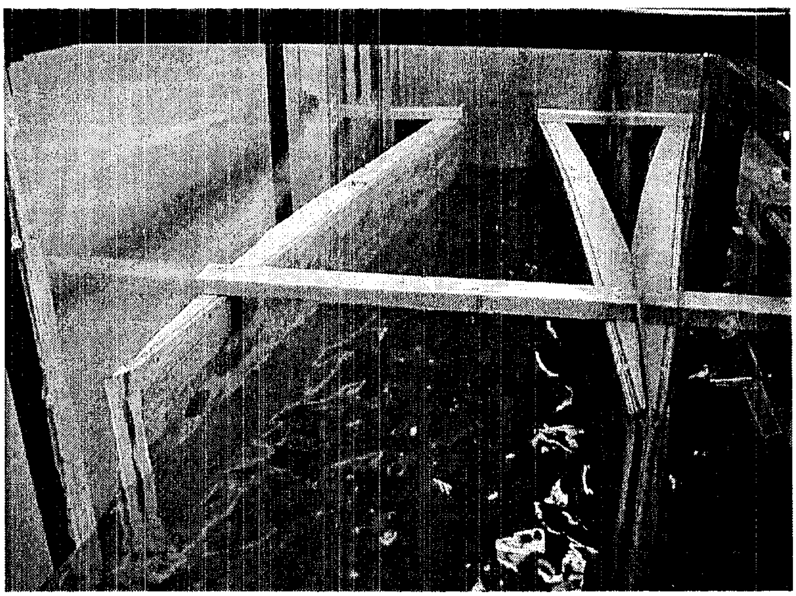

Photo 4. Converging Test Section

In addition to the large linear flume, a smaller flume, previously operated by UNM was available and used in selected tests. The dimensions of the small flume were 1-ft wide, 1.5-ft deep, and

10-ft long. The small flume was capable of testing insulation debris transport at full-scale transport velocities. The primary advantages of the small flume were 1) a uniform, calm and well-characterized flow throughout its length, 2) the debris were more visible due to the narrowness of its test section than was the wider large flume, and 3) it was relatively easy to clean fine debris, that could not be effectively filtered, from the flume and its sump (e.g., calcium-silicate dust). The small flume is shown in Photo 5.

The flume had two pumps with the combined flow capacity of approximately 100 GPM. Water was pumped from a small collection volume underneath the flume into the flume entrance and then allowed to drained back into the collection volume at the flume exit. Front and rear control gates were used to control flow height and velocity through the flume test section. The slope of the flume could also be varied. Conventional flow visualization/measurement techniques were used to assure that calm, uniform and straight flow patterns existed through out the flume length.

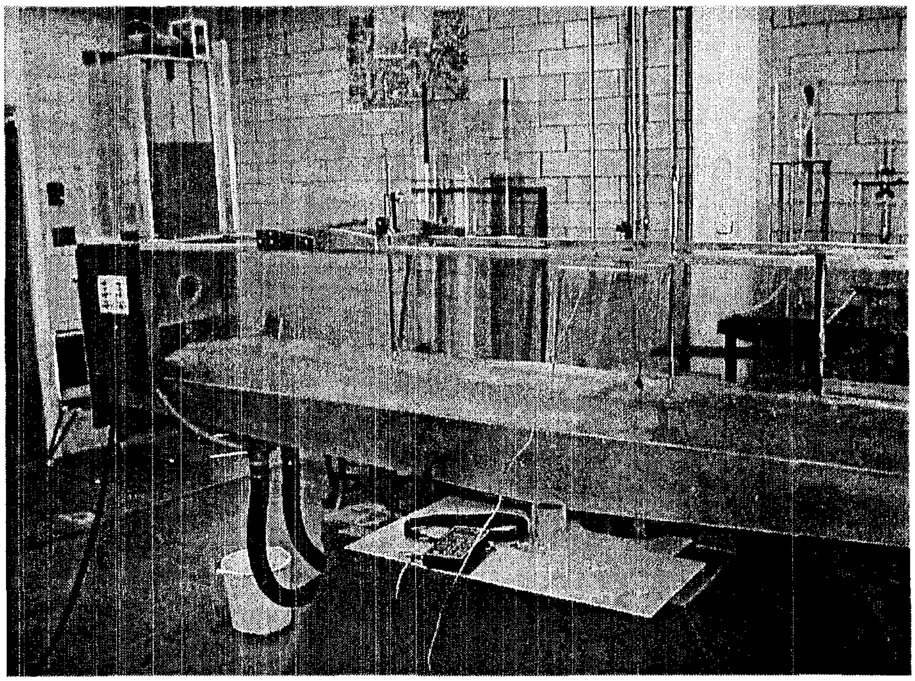

Photo 5. Small Flume Test Apparatus

Small flume was used extensively in the exploratory testing phase 1) to establish the importance of flume water height on debris transport, and 2) to develop test procedures that were ultimately used in the large flume. Comparison of small flume test data with the large flume test data also added a measure of quality assurance to the overall test data.

Terminal settling velocity measurements were performed by dropping pieces of pretreated debris of various types in a column of water and then timing their fall through a prescribed distance. The water column was constructed of Plexiglas and was 10-inches in diameter and 34-inches in height. The dissolution/decomposition behavior of calcium silicate, marinite and silicone-foam insulation fragments in water was investigated by dropping pre-characterized pieces into a large plastic cylinder filled with water to a height of 1-ft. Debris that did not disintegrate in the water, e.g. calcium silicate, settled into the tray placed in the bottom of the cylinder.

EXPLORATORY TESTING

An exploratory test program was conducted to develop test procedures and to identify important parameters for detailed testing, i.e., eliminate further testing of parameters shown to have little impact on debris transport. Thus exploratory testing examined: 1) the impact of water temperature, 2) the interdependency of mixed debris, i.e., the influence of one debris type on another, 3) the impact of flume height, 4) the importance of floor surface roughness, 5) the uniformity of the flow and the influence of non-uniformities on debris transport, 6) rather or not, vertical mixing was possible at higher velocities, and 7) repeatability of test data.

Because post-LOCA temperatures, ~80 °C, would be considerable warmer than the room temperature, water used in flume operation, the impact of water temperature was examined to determine the validity of conducting debris transport testing at room temperature. The temperature affects water density, surface tension, and viscosity and the saturation and potentially structural stability of the debris.

Water temperature can dramatically affect the time required to saturate debris placed in water. At room temperature, Nukon for example typically continued to float on the surface for more than a day. However, if the Nukon was placed in 80 °C water, it readily sank and remained submerged in as little as 2 minutes. Therefore, it was determined that debris would in general have to be pretreated before transport testing. That is, debris was soaked in hot in 80 °C water for a period of time before undergoing testing. A period of 5 minutes was found adequate.

Terminal settling velocities were measured in both 22 °C and 80 °C water for a variety of debris types and sizes. Exploratory tests determined that water temperature did not significantly impact the terminal settling velocity measurements; therefore all remaining measurements of settling velocities were conducted using room temperature water.

Water temperature was found to significantly influence the rate of dissolution of calcium silicate in water, therefore water temperature was retained as a test parameter in those tests.

Selected transport tests involving two different kinds of debris were exploratory tested to look for possible synergistic effects. Specifically, the transport characteristics of Nukon debris were examined to determine if the presence of fine calcium silicate particulate could alter either the terminal settling velocity or the tumbling velocity of pieces of Nukon. The presence of calcium silicate did not detectably affect either the terminal settling velocity or the tumbling velocity of Nukon.

The height of water in the flume was examined in both the small and the large flumes to determine if the water height needed to be retained as a test parameter. These exploratory tests led to the conclusion that the height of the water above the debris does not introduce a sufficient variation in the test results to warrant its inclusion as a test variable. Therefore, further floor transport tests were done with 18-inches of water height in the large flume.

A series of exploratory tests were performed to examine the impact, if any, of floor surface roughness, within the range of typical roughness for PWR surfaces, on floor debris transport. The transport of Nukon was tested for transport across both Plexiglas and plywood surfaces. The surface roughness did not have a statistically significant effect on floor debris transport for the conditions tested. Therefore, surface roughness was not retained as a test parameter.

The uniformity of the flow and the influence of non-uniformities on debris transport were examined with exploratory tests to develop an adequate method of dampening flow turbulences and non-uniformities. As dampening methods were tested, the uniformity of the flow was studied using both visual observations and qualitative measurements. Techniques included: 1) the tracking of dye injections, tracer particles, and air bubbles, 2) the measurement of local flow velocities using calibrated tracer balloons (calibrated in the small flume), and comparing debris transport results with data obtained by past investigators. Surface waves and large eddies observed prior to the use of dampeners and straighteners, were, for example, completely eliminated.

The question of rather or not debris could be vertically re-entrained by fast flowing water, i.e., the vertical mixing velocity, was examined during exploratory testing. Testing on both the small and large flumes using Nukon and aluminum RMI demonstrated conclusively that once the debris was on the floor and the flow conditions were uniform, the debris would not re-suspend itself into the flow. The debris remained close to the floor; therefore no further testing was conducted attempting to determine the vertical mixing velocities.

Exploratory testing was conducted to verify repeatability of debris transport data. Incipient motion tests were conducted for Nukon and steel RMI. These tests led to the decision to define incipient motion as movement of 6-inches or more in the first two minutes following an incremental change in flow velocity.

TEST RESULTS

Substantial quantities of test data were accumulated. The transport data was collected for the flow conditions of uniform flow velocities and low levels of flow turbulence. This data was collected in the small flume and a large flume configured for diffused flow entry, i.e., turbulence dampeners and straighteners in place (Configuration A). Summary diffused flow entry debris transport data is shown in Table 1.

Table 1. Summary Data for Diffused Flow Entry Inlet Conditions

Debris Type	Terminal Settling Velocity	Tumbling Velocities		2-Inch Curb Lift Velocity		6-Inch Curb Lift Velocity		Screen Retention Velocity
		Incip-ient	Bulk	Incip-ient	Bulk	Incip-ient	Bulk	
Calcium Silicate	0.13 to 0.17	0.25	0.35	No Data	No Data	No Data	No Data	No Data
Paint Chip	0.08 to 0.19	0.40	0.45	0.50	> 0.55	No Data	No Data	No Data
Al RMI	0.08 to 0.21	0.20	0.25	0.30	No Data	0.37	No Data	0.11
SS RMI	0.23 to 0.58	0.28	0.30	0.84	No Data	> 1.0	No Data	0.12
Nukon	0.13 to 0.41	0.12	0.16	0.25	No Data	0.28	0.34	0.05
Thermal-Wrap	0.08 to 0.22	0.12	0.16	0.25	0.25	0.30	No Data	0.04
Kawool	0.15 to 0.30	0.12	0.16	0.25	0.25	0.41	0.41	No Data
Marinite Board	0.44 to 0.63	0.77	0.99	No Data	No Data	No Data	No Data	No Data
Silicone Foam	Always Floats	N/A	N/A	N/A	N/A	N/A	N/A	N/A

A range of debris characteristics were found in the debris types tested; these characteristics ranged from the buoyant behavior of silicone form (silicone was found to always floats) to Marinite board, which readily sank. The terminal settling velocities for the types of debris tested are compared in Figure 1. Here the ranges of settling velocities, determined by timing the fall of pieces of debris through a specified distance in the water column, are shown as black bars. Of course, the heavier debris settled faster than the lighter debris. It should be noted that sizes and forms of debris different from the debris tested, might not fit within these ranges, for example, individual fibers of Nukon tend to settle very slowly, if at all.

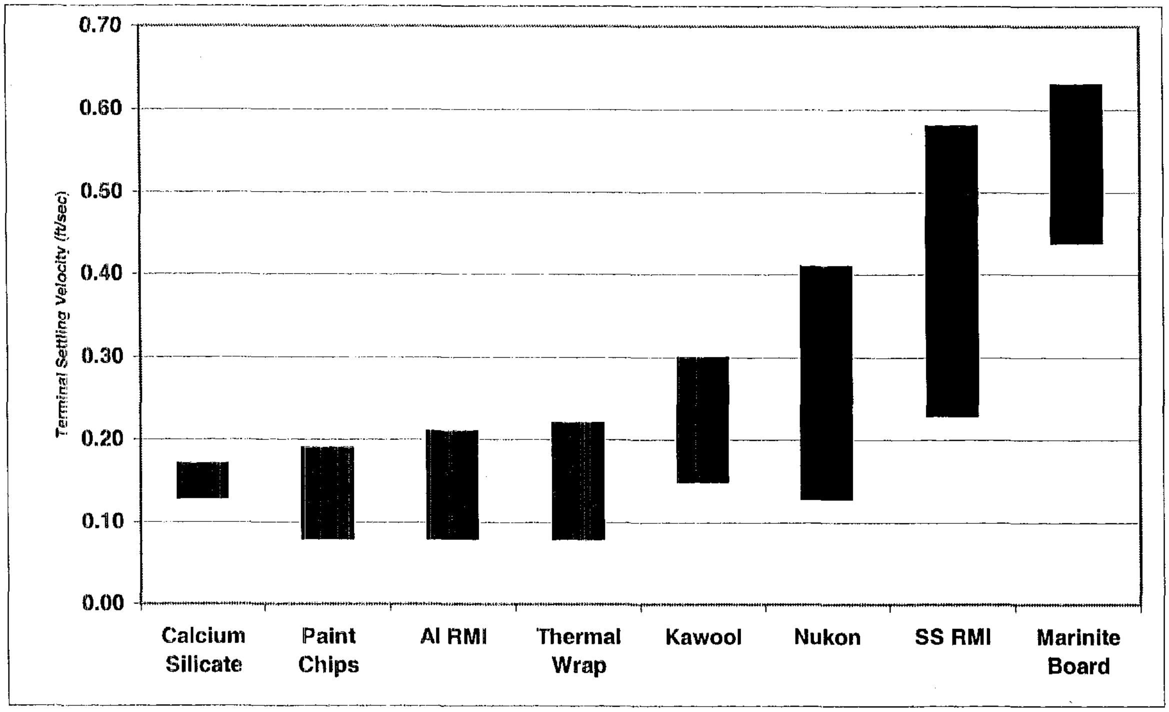

Figure 1. Comparison of Terminal Settling Velocities

The transport of debris moving along a floor was characterized by the flow velocity required to move the debris across the floor, referred to as the tumbling velocity, and the velocity required to cause the debris to jump an obstruction (curb), referred to as the lift velocity. These velocities were measured for onset of movement, i.e., incipient motion, and for bulk or mass movement of debris. The transport characteristics of incipient debris tumbling along the floor and the incipient lift velocities for transport of debris over an obstacle are compared in Figure 2. Again, these data are for flow conditions of uniform flow velocities and low levels of flow turbulence. The general rule was that it took a higher velocity to lift debris over a curb than to simply move the debris across the floor and the higher the curb, the fast the flow had to move to lift the debris over the curb. The heavier the piece of debris, the higher the velocity required for transport and the larger the difference between the tumbling velocity and the lift velocity. SS RMI, for example, took a substantially faster flow to lift the debris over a curb than to simply move it across a flat floor.

For most debris, the velocity differences between incipient and bulk motion were not substantial, that is, once the debris started to show movement (incipient), a relatively modest increase in velocity induced bulk movement of debris. This point is illustrated in Figure 3, which compared the incipient tumbling velocity to the bulk tumbling velocity for the different types of debris tested.

The flow velocity needed to keep a piece of debris on the screen was less than the velocity needed to initiate transport of the debris to the screen. In general, the measured screen retention velocities, listed in Table 1, were less than half the incipient tumbling velocities. Therefore, once debris arrives at the screen, it can in general be expected to stay on the screen.

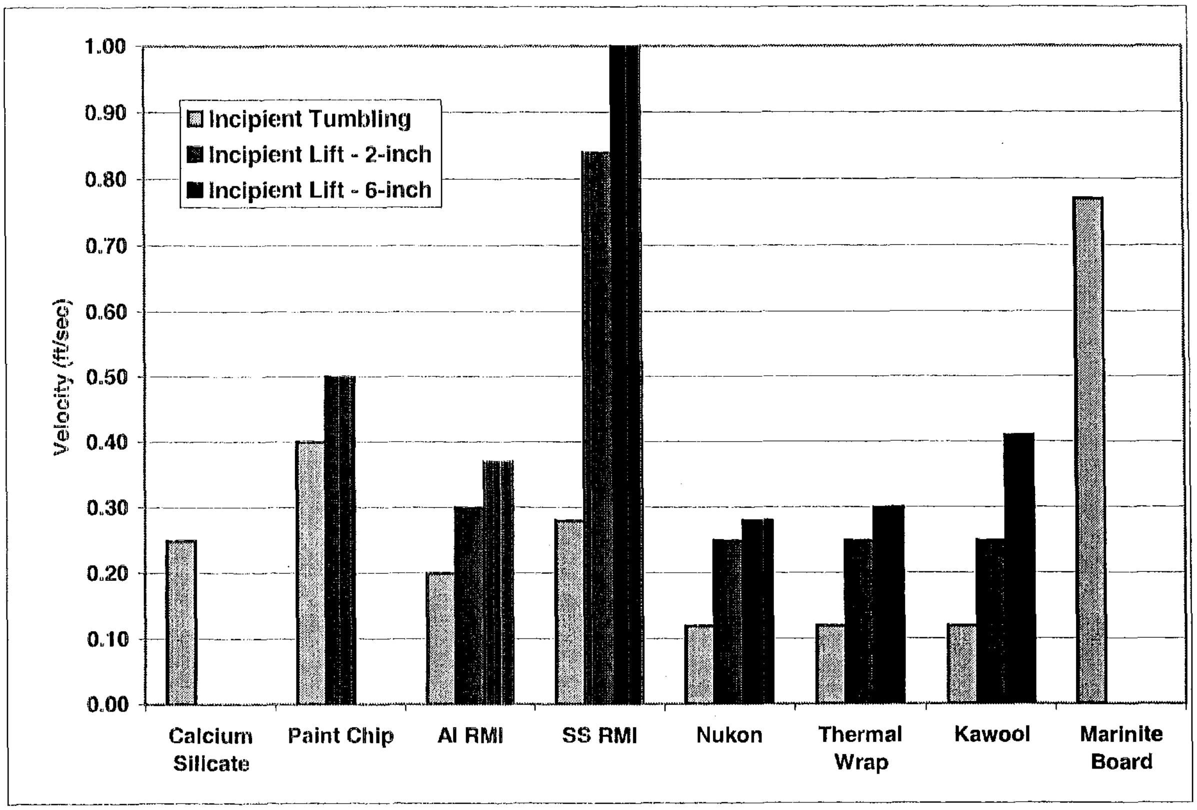

Figure 2. Comparison of Transport Velocities

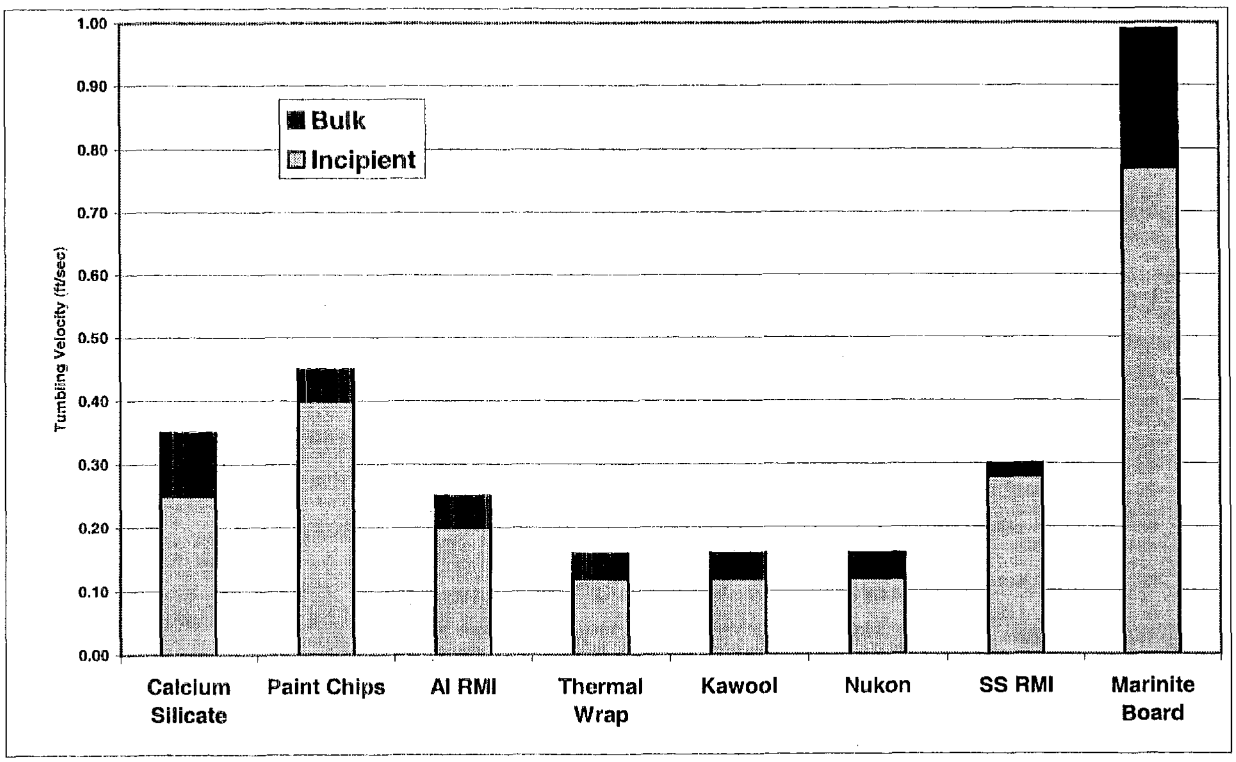

Figure3. Comparison of Incipient and Bulk Tumbling Velocities

Debris transport was also tested for alternate inlet flow conditioning configurations to examine the impact of turbulence and non-uniform flow condition on debris transport. The summary debris transport data shown in Table 2 compares incipient transport velocities of debris tested in the large flume for each of the inlet flow conditioning configurations A, B, and C. These data are compared graphically in Figures 4 and 5, for the tumbling and lift velocities, respectfully.

It was difficult to draw conclusions regarding the impact of inlet flow conditioning configurations. It is important to keep in mind that these measured velocities were flume averaged flow velocities.

Table 2. Summary Velocity Data Comparing Turbulence and Non-Uniform Flow Effects

	Incipient Tumbling			Incipient Lift–2" Curb			Incipient Lift-6" Curb		
Debris Type	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Thermal-Wrap	0.12	0.07	0.10	0.25	0.25	0.22	0.28	0.25	0.30
Kawool	0.12	0.09	0.17	0.25	0.25	0.28	0.41	0.25	0.32
Nukon	0.12	0.07	0.06	0.25	0.25	0.22	0.28	0.25	0.28
Steel RMI	0.28	0.37	0.20	0.84	0.90	1.0	>1.0	1.0	>1.0

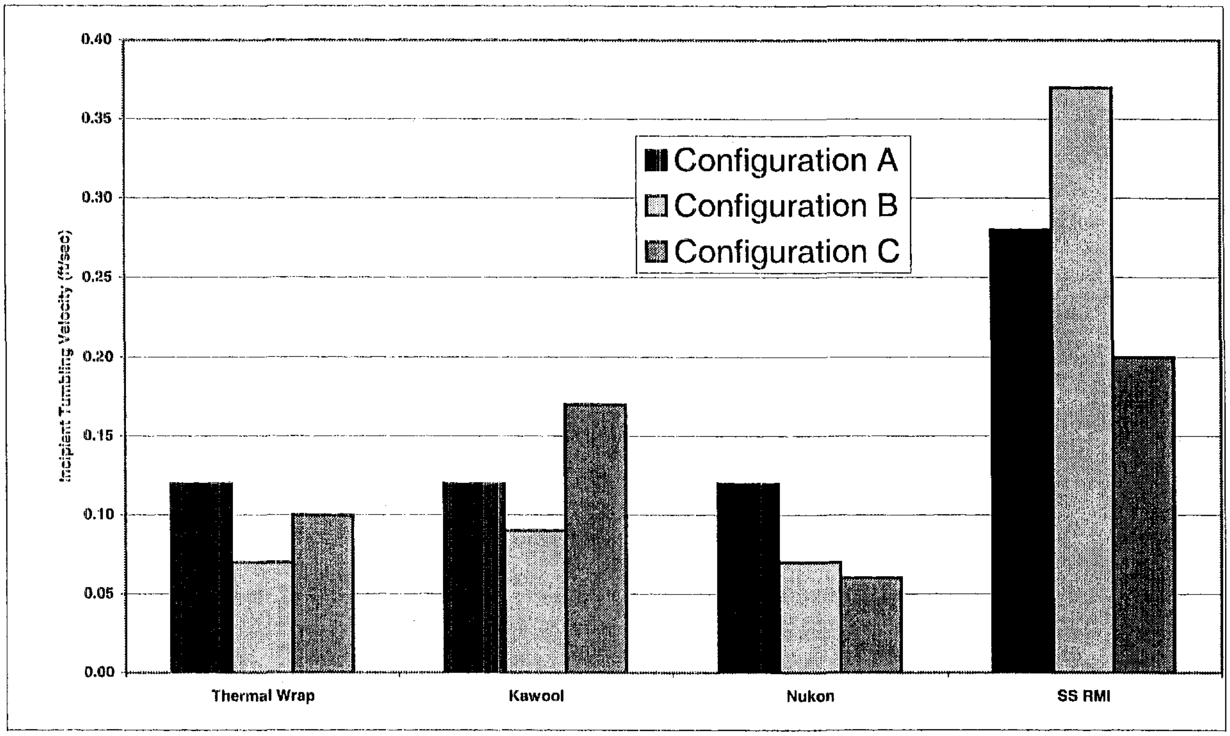

Figure 4. Comparison of Tumbling Velocities Versus Inlet Flow Configurations

Only in Configuration A did the average flow velocities reasonably reflect the local flow velocities, i.e., the flow velocity around the individual pieces of debris under study. With Configurations B and C, the local flow velocity were likely either somewhat faster or somewhat slower than the average velocity. Given this situation, it should be expected that trends associated with Configurations B and C would be somewhat erratic. For example, the incipient tumbling velocity for Kawool was slower at 0.09 ft/sec in Configuration B than the 0.12 ft/sec for Configuration A. But Configuration C was faster at 0.17 ft/sec than was Configuration A.

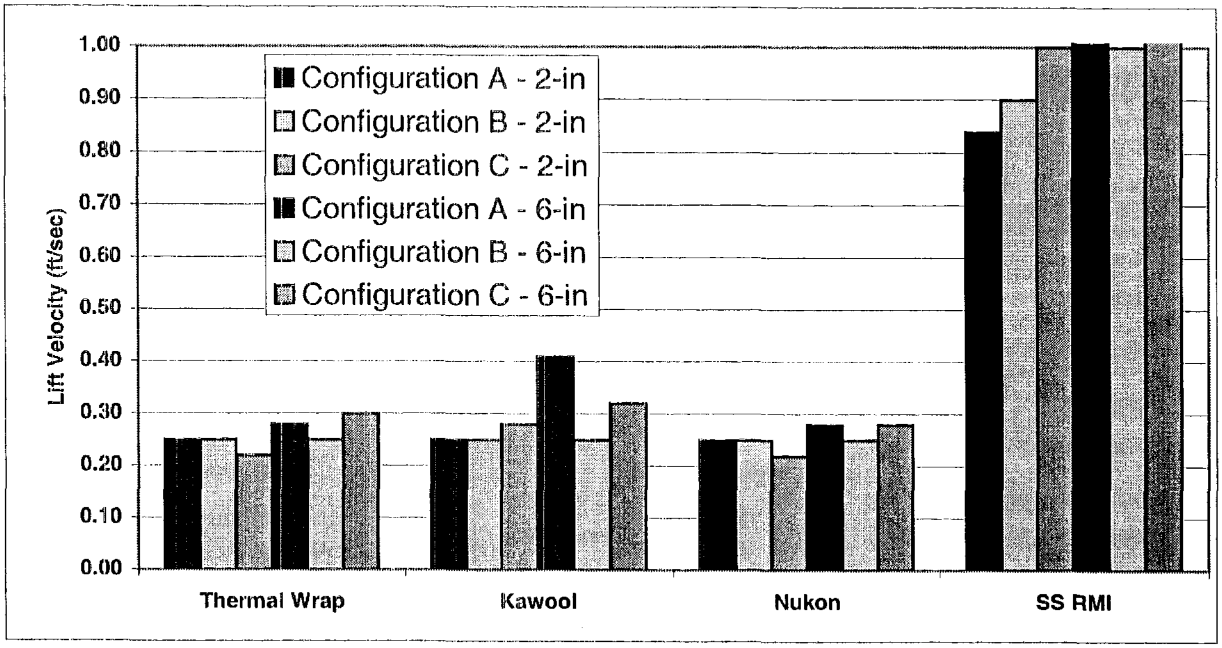

Figure 5. Comparison of Lift Velocities Versus Inlet Flow Configurations

In converging flume tests, where the flow cross-section was altered to force the flow to accelerate by converging the sidewall, debris transport was tested for selected conditions. Tests were conducted using steel RMI, aluminum RMI, and Nukon. Debris was dropped at a number of locations along the converging flume. Data suggests that the act of accelerating the water did not impact the transport of the debris. Rather, debris transport behaved according to the flow velocity at its current debris location.

The only debris tested for which substantial decomposition behavior was noted, was calcium silicate. Substantial quantities of calcium silicate debris were found to disintegrate when dropped into water and the degree of disintegration increased with water temperature. This disintegration data (the averages and the ranges) is shown in Figure 6.

Debris dropped into was allowed 20 minutes to disintegrate. The water temperature was either room temperature or heated to 80°C. In some of the 80°C tests, the water was stirred by hand. Just dropping the debris in 80°C water, approximately 50% of the debris mass was suspended in the water within 20 minutes. Stirring the water increased the disintegration process. It must be concluded that calcium silicate dropped into a hot containment floor pool for extended time and possibly undergoing turbulent churning will most likely disintegrate into fine particulate that easily remains suspended.

While not disintegrating, pieces of Marinite board became soft and with a rubbery texture on the exposed surfaces when submerged in boiling water for 30 minutes. A very small amount of milky whitish substance was released when the wet material was rubbed. Small pieces of material, smaller than ¼-inch, could be pulled from the wet surfaces. These small pieces readily sank. Considering the amount of plastic deformation required to pull these rubbery pieces apart, the disintegration of Marinite into smaller fragments due to flow turbulence is highly unlikely.

Silicone foam was obtained after it had been mixed and foamed in a 5-gal bucket by the supplier. Irregular pieces, roughly 2-inched cube, were cut from the buckets for testing. Foam pieces were forcefully immersed in 80°C water for 10 minutes, boiling water for 15 minutes, squeezed under water to force out remaining air, then re-submerged and kept submerged for 3 days in room temperature water. After all this, the pieces of foam always continued to float.

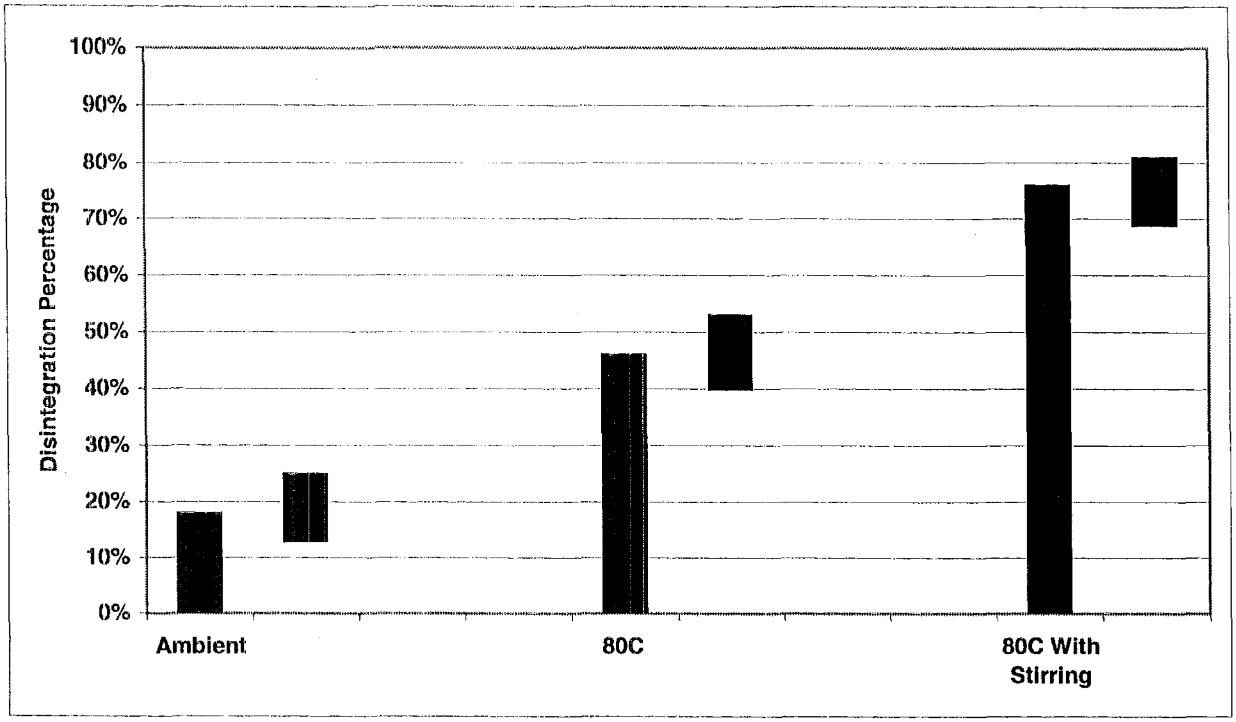

Figure 6. Disintegration Data for Calcium Silicate

Intact steel RMI cassettes were tested to determine the time required for a cassette to sink and the flow velocity required to push a cassette across the floor. A slotted cassette sank in 5 minutes and a cassette with solid closures sank in 13 minutes. No floor transport was observed at the flow velocity of 0.5 ft/sec but some transport was observed at 1.0 ft/sec.

Five intact pillows of thermal-wrap insulation were tested to determine their terminal settling velocity after forcibly soaking them for 24 hours. The settling velocities ranged from 0.25 to 0.54 ft/sec.

A substantial quantity of basic debris transport data was accumulated in these tests, thereby fulfilling the experimental objectives. It is anticipated that an overall methodology can now be developed that will combine this database with CFD analyses to predict debris transport within a containment floor ECCS pool.